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A system dynamics approach to evaluate the impact of traffic management policy to urban air quality

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Abstract

Alleviating urban traffic problems is one of the most practical approaches to improving urban air quality. A system dynamics approach was used to integrate three sub-models to evaluate the impact of urban NO_x and HC emissions from traffic management policies. The three sub-models are the Logit model for estimating the fleet composition from user's preference, the traffic flow model for estimating vehicular speed and the traffic emission model for estimating the individual vehicular emissions from scooters, cars and buses. The application of the system to evaluate the impact of traffic management policies to Taipei City's traffic and air quality was demonstrated. Five policies, namely the exclusive bus lane, bus fare compensation, rescheduling bus route frequency in peak and normal periods and compulsory carpooling were considered in this study. The evaluation shows only compulsory carpooling and bus fare compensation policies result in reducing both NO_x and HC emissions. For the rest of the policies, they result in either NO_x reduction while increasing HC emissions or HC reduction while increasing NO_x emissions.

1. Introduction

In most cities, clean air and the smooth traffic are two key indexes of urban living quality. Alleviating urban traffic problems is an important strategy for improving urban air quality. In most urban areas, mobile emissions are usually the major source of air pollution. In Taipei ,it was estimated that 90 % of HC, 94 % of NO_x and 99% of CO emissions are from vehicles. In Europe the 1995 data [1] show that the traffic sector contributes 65% emissions of NO_x. Although there is a huge variation of emissions among the cities of the European countries, mobile emissions contribute at least 39% of the total air pollutant emissions [1].

To improve air quality in an urban area, one needs to effectively control mobile emissions. Mobile emissions are highly related to traffic conditions.

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Three control factors to mobile air pollution are vehicular number, vehicular speed and its emission rate. The three factors are highly interrelated. First, the vehicular speed is inversely proportional to the number of vehicles in use because of the limited road capacity. Second, the quantity of air pollution is a function of vehicular speed and number. Since there are multiple vehicles types in use, the quantity of air pollutant emission is a function of fleet compositions and the individual vehicular numbers and speed.

To evaluate the effect of traffic management policies on air pollution involves two stages. The first stage is to assess the traffic outcome that is impacted by the policies. The second stage is to evaluate air pollution emission changes from the impacted traffic outcome. The complexity of the first stage comes from the impact of traffic policies on the traffic flow, namely the redistribution of fleet composition and individual vehicular numbers and speed. The second stage involves the complex relationship between the individual vehicular speed and the vehicular emission characteristics of air pollutants. An assessment tool that can handle these complexities is required when performing the policy impact evaluation. Past studies regarding to the problem focus on issues related to either the individual stage or the whole problem. Several studies developed a calculation model for the problem in the second stage [2][3][4][5]. The other study applied an integrated model for the whole problem [6].

In this paper, a system dynamics approach is proposed to evaluate the impact of traffic management policies to urban air pollution and its application in Taipei City case study was performed.

2. Model Methodology

A model that integrates three sub-models, namely a user's choice model, the traffic model for vehicular speed and number, and the traffic emissions model, was proposed to estimate the impact from traffic management means to the change of HC and NO_x emissions in an urban area. The three sub models are illustrated in Fig. 1. They are Logit sub-model for estimating fleet composition from user's preference before and after imposed traffic management policy. The traffic flow sub-model is for estimating the average speed of each on-road vehicle in the above fleet composition. The traffic emissions sub-model is for estimating individual vehicular emissions from above estimated vehiclar speed and composition. In this study only three vehicles (scooters, cars and buses) and two emissions (NO_x and HC) are considered.

The three submodels then were integrated by the system dynamics approach to build an interrelated system. The system can be used to simulate the temporal and spatial interaction between traffic conditions and that traffic emissions. In the following, details of the three submodels are described.

2.1. Logit Mode

This submodel was used to determine a user's preference in his vehicle choice. The user's preference is parameterized as a utility function of influential factors. The equation (1) was used to calculate the utility of factors.

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$$U_{it} = \sum_{k} X_{ikt} \beta_{kt} \quad (1)$$

where the U_{it} is the utility for user t and tool i, A_t is the set of alternatives, the X_{ikt} and • $_{kt}$ are the variable and the coefficient of utility function separately. The equation (2) is used to calculate each vehicle's chosen probability.

$$P(i : A_t) = \frac{e^{U_i}}{\sum_{j \in A_t} e^{U_j}} \quad (2)$$

where the $P(i{:}A_t)$ is the probability that a user t will choose option i from the collection A_t. The considered factors are cost, travel time and comfort level, as shown in Fig. 2. The index for the cost factor is the cost/income ratio, and the time-in-car and time-out-of-car/distance ratios. Space, weather and ride are three indexes to reflect comfort level. One assumption of the Logit model is that the considered factors can be traded off. Therefore a linear equation is used to combine the considered factors of every vehicle and a user's choice can be estimated by the chosen probability or the utility value.

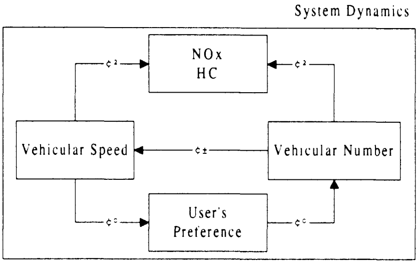

Figure 1: System dynamics model modules, interface and structure

The cost factor includes the cost of purchase and operation of a vehicle. The operation cost contains gasoline, tax and the maintenance cost. The cost will be normalized to average personal income in order to reflect the relative cost consideration of an individual vehicle user. In general, a richer user tends to select a higher cost vehicle in the situation when the travel cost in increased.

The time-in-car factor reflects the user's consideration of available vehicular speed. It is an important factor for a user in selecting which type of vehicle for travel. For bus users, its time-out-of-car includes bus waiting time and the time for walking to the bus station. For private car users, the factor includes the time for parking and walking to the parking site. The time that is spent outside the cars is normalized with the total travel distance. Usually a user who travels longer distance tends to be willing to spend more time for waiting and parking than a user who travels shorter distances.

The comfort level was uses to model the subjective prejudice of vehicle choices. Among the three factors the space factor reflects the privacy and spaces that a user shares in his chosen vehicle. The value of this factor is 1 for selecting a private car or scooter and is 1/30 for the bus user. The weather factor reflects the disadvantage of the scooter compared with the car or bus on a rainy or hot day. The ride factor reflects the effort required from each vehicle user. It reflects that the bus users require no effort to drive when compared

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with the car or scooter users.

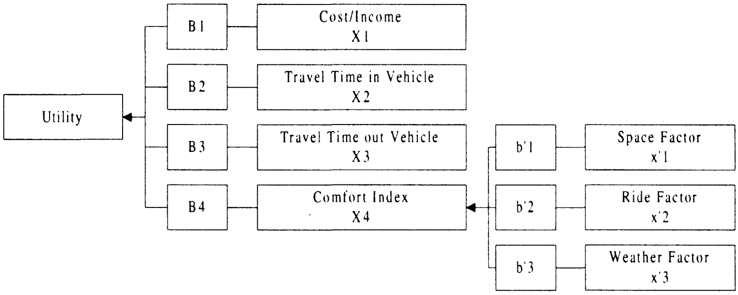

Figure 2: Scheme of vehicle choice calculation in the Logit submodel.

2.2. Traffic Flow Model

For the traffic flow, equations (3) and (4) are used to calculate the average speed of each vehicle in a finite road space and vehicle composition. In the model, the average vehicle speed was calculated from a free speed and traffic density, as described by Equations (3) and (4),

$$V = V_f \times e^{(\frac{-K}{K_m})} \qquad (3)$$

$$K_m = \frac{K_j}{e} \qquad (4)$$

where Km is the vehicular density and V_m is the individual vehicular speed at maximum traffic flow. V_f is the free speed and Kj is the jam density. The free speed is a vehicle's speed when no other vehicle interrupts it. The jam density is the number of vehicles in a unit distance when the average speed is zero. With the output of the Logit sub-model, the fleet composition, then the individual on-road vehicle speed can be calculated from the traffic flow sub-model.

Since three optional vehicles are always on road at the same time, the number of scooters and buses are converted into the equivalent size of the cars. Therefore only one total density is used to reflect the on-road vehicle density. The equivalence factor of scooters and buses is 0.3 and 2.5 respectively. Fig. 3 shows the relationship of the total vehicular density and the speed of three types of vehicles. The individual free speed and jam density were used to reflect that the individual vehicular speed may be different at the same total density; buses sometimes may be congested, while scooters still can keep moving in the same flow density.

2.3. Traffic Emissions Model

The emissions are assumed to be function of vehicular speed, as described by equation (5):

$$Y = a + bv + cv^2 \qquad (5)$$

where Y is the coefficient of emissions (g/km), V is the speed (km/hr), and a, b and c are the coefficients for different vehicles. Since different engine designs

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and sizes may cause different emissions, the vehicles were categorized by engine size into three types of scooters and four types of cars. The considered emitted air pollutants are NO_x and HC. Fig. 4-6 illustrated the relationship between emissions of pollutants and speed for every type of vehicle. The NO_x emission increases as the vehicle is increasing its speed, while the HC emission tends to decrease as the vehicular speed increases.

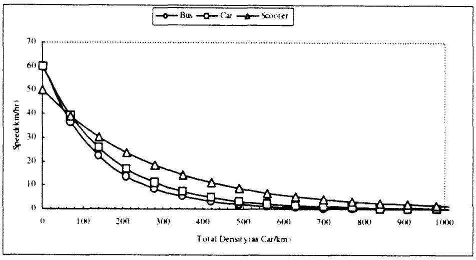

Figure 3: The relation of total traffic density and vehicular speed.

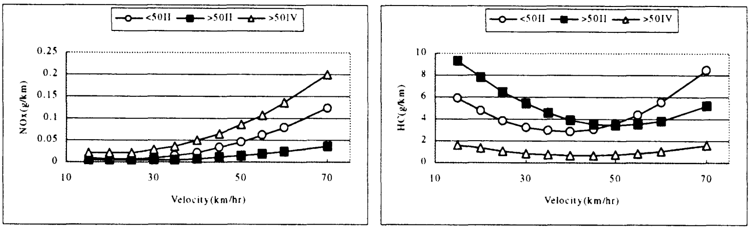

Figure 4: Relation of emission coefficient with scooter speed.

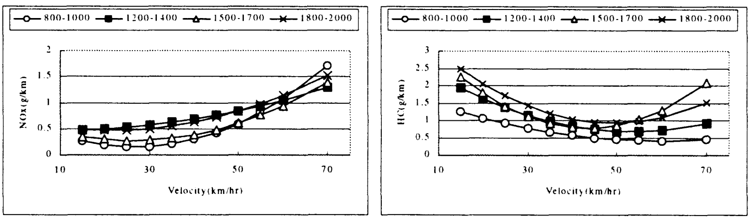

Figure 5: Relation of emission coefficient with car speed.

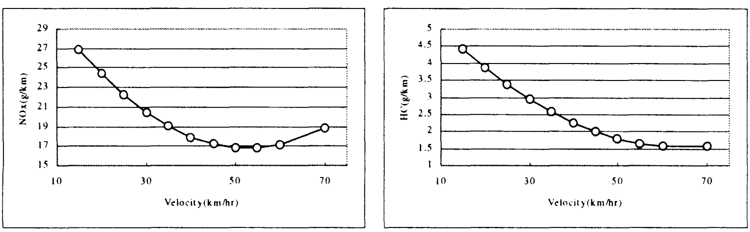

Figure 6: Relation of emission coefficient with bus speed.

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2.4. System Dynamics

A causal feedback loop diagram (CFLD) is used to describe the procedure of NOx/HC emission calculation and the relevant data flow as shown in Fig. 7. Detail causal relationships in the diagram are described as below.

1. User's choice of vehicle type was simulated by Logit model that considered three factors, namely the comfortable level, travel time and cost/income ratio. The Logit model is used to estimate the probability of user's choice of three vehicle types while the factors considered above then feedback through the system to influence user's choice for the next stage.
2. The vehicular speed and vehicular number were calculated by traffic flow model. The estimated traffic flow then feedback to travel time and comfortable indexes of Logit model and indirectly influence the user's next choice of vehicle types.
3. The NOx/HC emissions were calculated from emission model by inputting vehicular speed and vehicular number calculated from above. The emissions can be calculated at the time when there are outcomes from the Logit and traffic models.

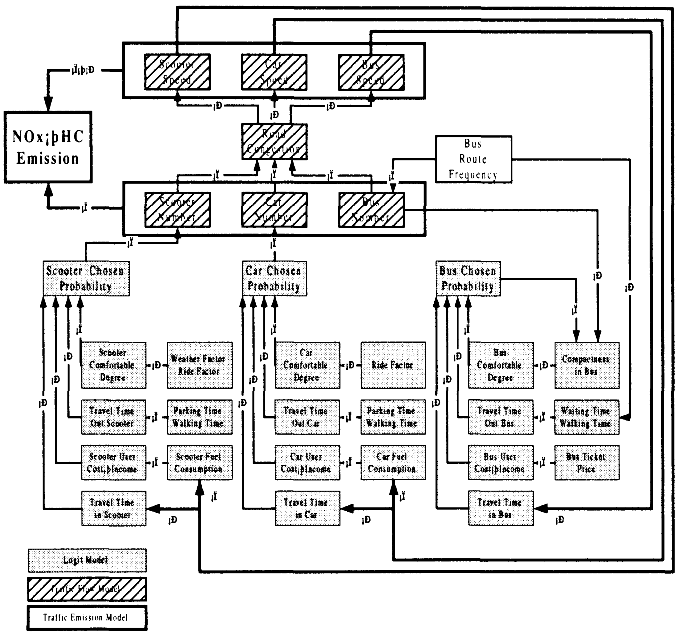

Figure 7: Components of the system dynamics-based evaluation system

The procedures were iterated until all the users satisfy their choice of vehicle then the system reaches a new stable stage. The system then was used to compare the NOx and HC emissions at original stage with those at the new stage to evaluate the emission difference caused by the imposed traffic management policies. Four case studies were simulated and evaluated in this study. The traffic management policies considered in the case study are: 1. Exclusive bus lane, 2.Compensation for bus fare, 3. Change of bus schedule, 4.

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Compulsory carpool. The simulation results then were used to assess the consequences of air quality and traffic conditions when the evaluated policies were implemented.

3. Results and Discussion

To validate the model whether it can reflect normal daily air quality of Taipei, the model was first used to simulate the temporal distribution of each air pollutant for each vehicle, as shown in Fig. 8. Two peaks of emissions were found during the peak traffic load periods. This verifies that the model can reasonably simulate the current air quality status. Based on the current air quality status, the considered traffic management policies were evaluated by simulation and comparison. They are discussed subsequently in the following.

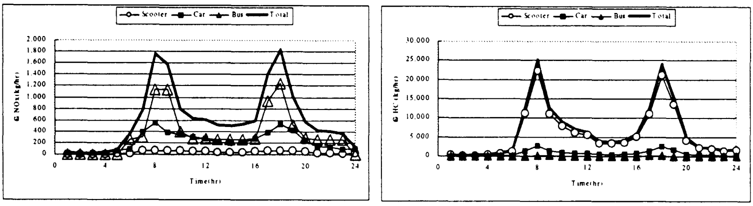

Figure 8: Temporal distribution of NO_x and HC emission simulation.

3.1. Exclusive Bus Lane

Providing exclusive bus lanes usually can reduce the overall traffic density such that the available space for private vehicles may be reduced. Reducing the available space for private vehicles then lowers the number of on-road vehicles. In this simulation, 26% road area was separated to perform the exclusive bus lane and the rest was opened for all vehicles. The implement of exclusive bus lane result in increased bus speed and decreased car number. This encourages part of private car users to turn to use bus and scooter that results in more congested on the non-exclusive bus lane road. It is found that the daily NO_x emissions were decreased while the HC emissions were increased as shown in Fig. 9. The decreased NO_x emissions are due to the increased bus speed that is within the decreasing NO_x emissions speed range, while the increased HC emissions are due to the increased scooter number. The increased scooter users are from two sources, the users shifted from bus users because of the limited bus capacity and the users shifted from car users because of the congested traffic.

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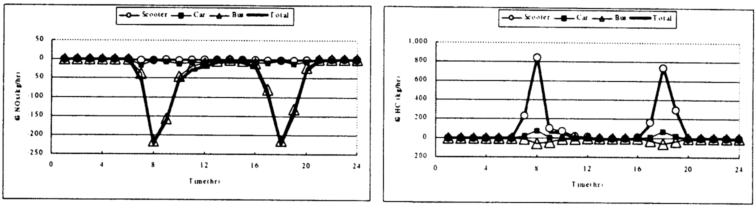

Figure 9: The change of NO and HC emission when an exclusive bus lane policy is implemented.

3.2. Bus Fare Compensation

When the compensation for bus fares is implemented (free bus fare), many users tend to select bus for travel. This then significantly reduces the number of on-road private vehicles and increases the overall vehicle speed. Since there are more buses available during rush period than normal period, users who want to shift from private vehicles to buses during the rush period have more chances than during the normal period. From Fig. 10, it is found that the combination contribution of the vehicle distribution and vehicular speed resulted in a reduction in daily NO_x emissions. The main factor that causes the reduction of NO_x emission is the reduction of on-road private cars. The reduction of HC emissions is mainly due to the decreasing number of scooters.

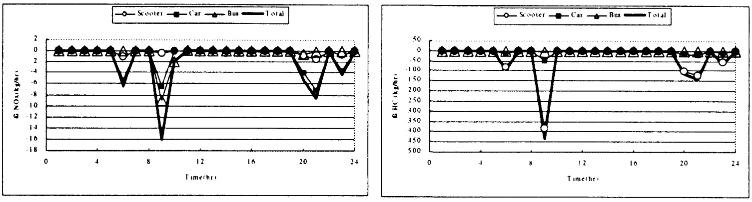

Figure 10: The change of NO and HC emission when a bus fare compensation policy is implemented.

3.3. Reschedule Bus Route Frequency

The bus schedule is usually arranged such that there are different route frequencies during peak periods and normal periods. Too many on-road buses will congest traffic and reduce the overall traffic speed, while too few on-road buses will increase the out-of-car travel time for bus riders. In this study, the peak period was defined for the 7-9 a.m. and 16-18 p.m. periods while the rest are the normal traffic periods. If bus route frequency interval for the peak period is rescheduled from 5 minutes to 15 minutes, it was found that the fleet composition was redistributed. At first users tend to give up selecting bus because of the increased out-of-car travel time. Then car users tend to shift to choose scooters because that the increased number of cars and scooters results in the slowing down of overall traffic flow. In Fig. 11, it is found the overall NO_x emissions reduced after rescheduling bus route frequencies. The accommodation between the increased number of cars and scooters that increasing NO_x emission with the reduced bus speed that decreasing NO_x

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emission results in the reduction of total NO_x amount. On the contrary, the HC emissions increased because of the increased number of on-road cars and scooters.

The next simulation was performed for rescheduling bus frequency from 15 minutes to 5 minutes during the normal period. This is expected to reduce out-of-bus time and to increase the bus supply in normal period. The simulation results, as shown in Fig. 12, indicate that the traffic flow becomes congested as the on-road buses increase in the beginning phase. Once the user shifts to the bus, both the on-road cars and scooters are reduced, and the overall traffic flow then is improved. The increased number of buses and their speed result in increasing NO_x emissions while HC emissions are reduced because of the reduced scooters.

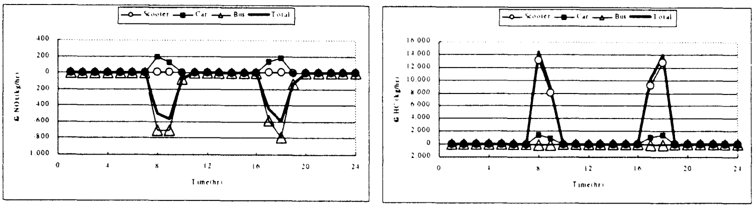

Figure 11: The change of NO and HC emission when a policy reducing bus route frequency in peak periods

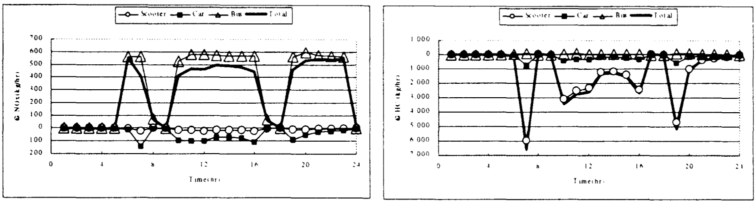

Figure 12: The change of NO and HC emission when a policy increasing bus route frequency in normal periods is implemented.

3.4. Compulsory Carpool

A compulsory carpool policy that allows only cars with three or more passengers to be on the road in Taipei City was evaluated. The simulation shows that two consequences occurred when implementing the compulsory carpool policy. First, the number of single-occupant private cars was reduced and the overall speed of on-road vehicles was increased. This result in reduced overall emissions of both NO_x and HC as shown is Fig. 13. The reduced HC emission is due to the reduced number of on-road cars and the increased speed of scooters and cars, while the reduced NO_x emission is mainly due to the accommodation between the reduced cars and the increased vehicle speed. Because the reduced number of cars will result in reduced NO_x emission while the increased vehicle speed will result in increased NO_x emissions, the accommodation between the two driving force come up with reduced overall NO_x emission as shown in Fig. 14.

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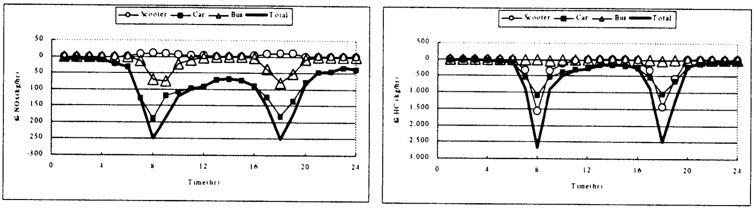

Figure 13: The change of The change of NO and HC emission when a compulsory carpool policy is implemented.

4. Conclusion

A system dynamics-based policy evaluation system which integrates estimation of traffic flow, traffic emissions with traffic conditions and user's choice of vehicle was proposed and demonstrated to evaluate the impact to urban NO_x and HC emissions by traffic management policies. Five policies, namely the exclusive bus lane, bus fare compensation, rescheduled bus route frequency in peak hours and off-peak hours and compulsory carpool policy implementation, were simulated and evaluated. Among the five policies, only compulsory carpool and bus fare compensation result in reducing both NO_x and HC emissions. For the rest of the policies, the simulation results as shown in table 2 indicate that they are either reduced NO_x emissions while increasing HC emissions, or reduced HC emissions while increasing NO_x emissions. The impact of the exclusive bus lane policy was expected to reduce NO_x emissions by 7.2% and increase HC emissions by 1.5%. The proposed system can be extended to evaluate urban air quality improvement when introducing new traffic infrastructure such as a mass transit system.

Table 2: Summary of traffic emission changes for all evaluated policies

	Policy	• NOx(%)	• HC(%)
1	Exclusive Bus Lane	-7.2%	1.5%
2	Compensation of Bus Fare	-0.3%	-0.5%
3	Reduce bus route frequency in peak period	-15.2%	29.8%
4	Increase bus route frequency in normal period	46.3%	-18.1%
5	Carpool	-13.9%	-7.3%

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